Modeling of aerodynamics of flapping wings and blades using high-order of approximation numerical schemes and Lattice Boltzmann method

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"Use of a Pitching and Plunging Cascade for Thrust Generation"

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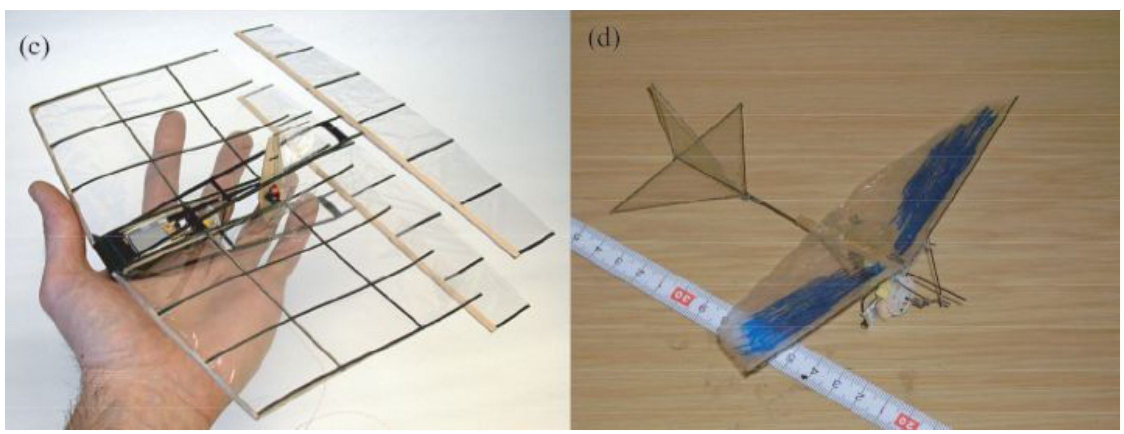
Why to use flapping wings for Micro Air Vehicles (MAV)?

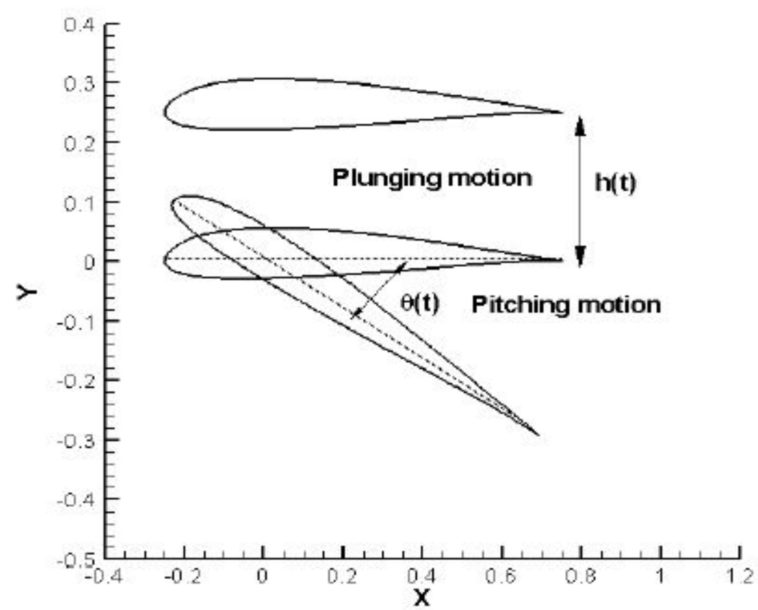
Superior flight characteristics exhibited by birds and insects with a wingspan at or below 15 cm can be taken as a prototype of the most perfect form of flying machine ever created.

The size of a MAV and its speed of operation result in relatively low Reynolds number flight which is far below the flying conditions of a conventional fixed-wing aircraft.



Current research: Goals and Motivation

- A modified version of the pitching motion (compared to traditional pitching about a fixed axis of rotation) has been investigated to increase lift and thrust components of aerodynamic force.
- The goal is to find kinematic motions of wings to increase the lift force at relatively low values of reduced frequencies and amplitudes by modifying the kinematic motions of wing.
- To create thrust, a generalized pitching motion combined with plunging motion is proposed and studied.
- Response of pitching and plunging wing to flow gust is studied.



Governing equations and high-order of approximation numerical method

- unsteady Navier–Stokes solver (direct simulation)
- non-inertial coordinate system moving with the airfoil

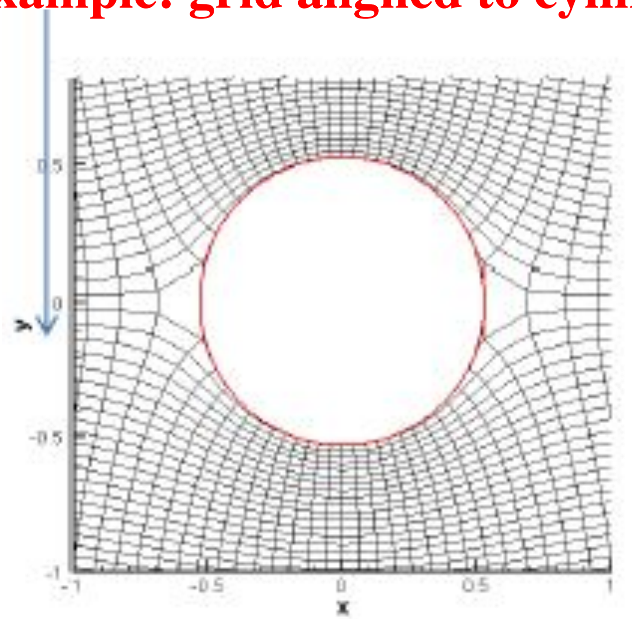
The current solver uses:

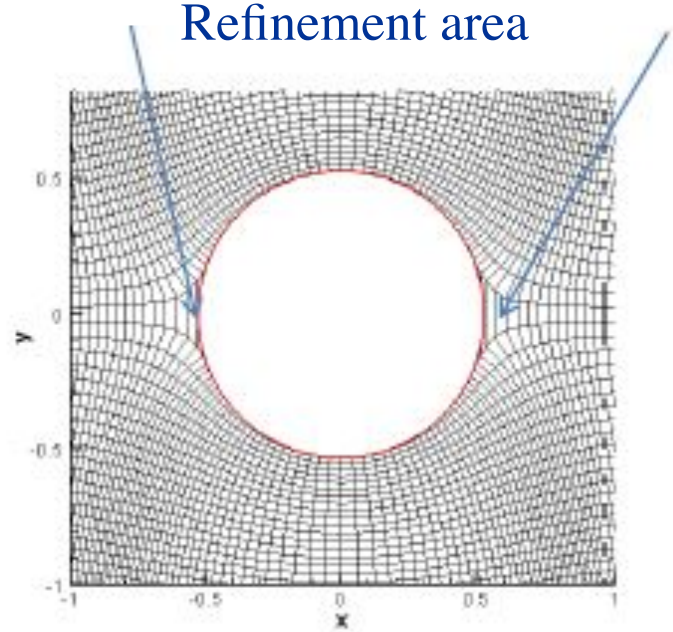
- fourth-order compact central differences for spatial discretization
- Tenth-order implicit filter to filter the unresolved wave numbers and to avoid numerical oscillations
- a third-order low-storage explicit Runge–Kutta scheme for integration in time

Grid generation: cluster grid near stagnation points and at boundary layer

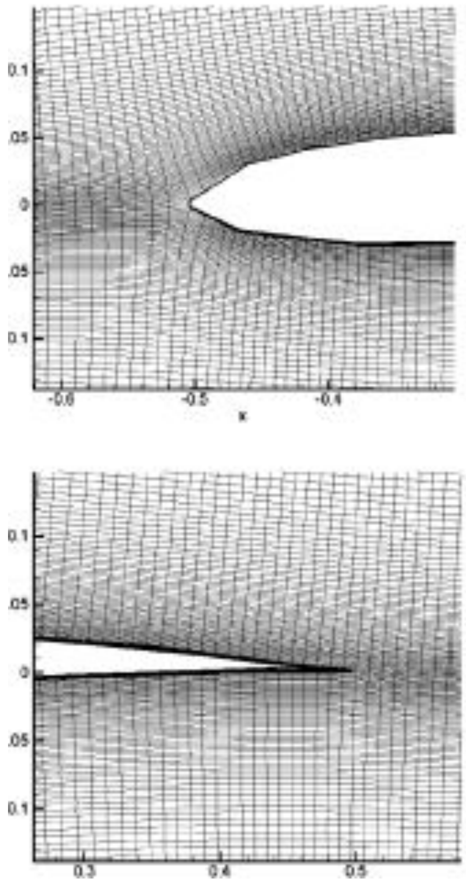
- The streamfunction and potential function are orthogonal to each other. This allows the streamlines and potential lines to be used for the generation of boundary-fitted grids.
- Orthogonal grids are generated using numerical panel method.
- To reduce the size of coarse cells near the stagnation point, the potential lines are clustered using hyperbolic sine function.

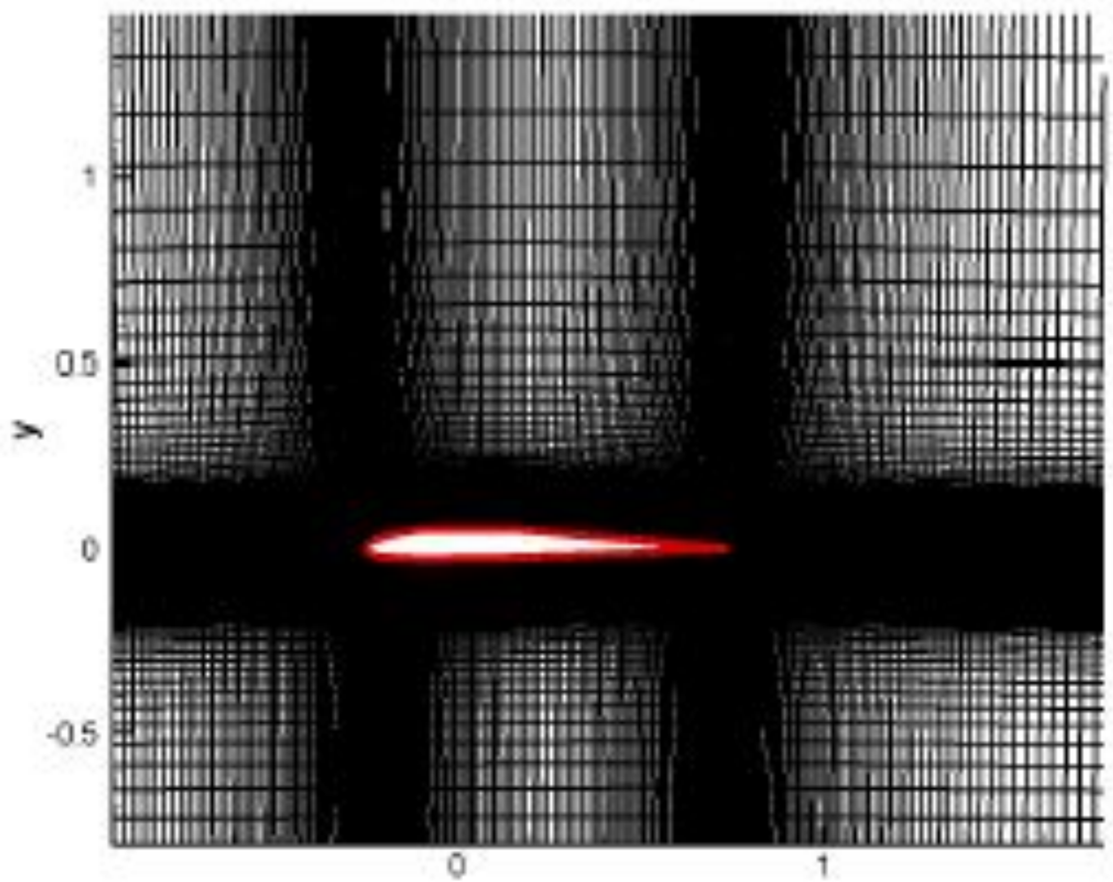
Example: grid aligned to cylinder





Numerical grid aligned to airfoil is generated using streamlines/potential lines obtained from inviscid flow solution.



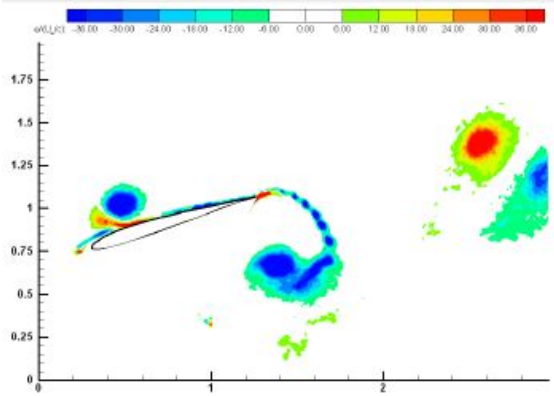
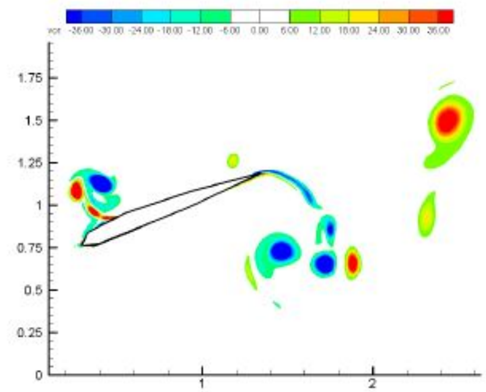
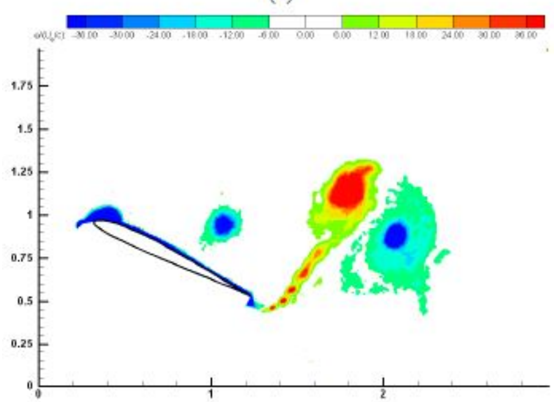
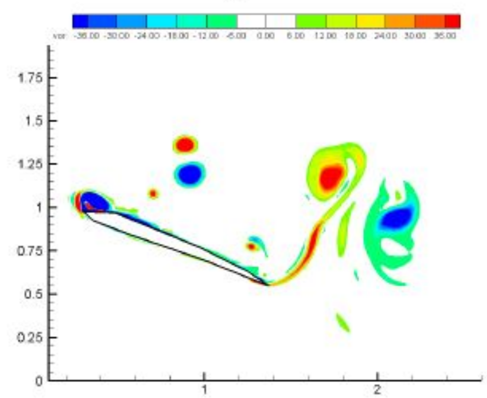


300 x 100 *H-grid*

See H. Gopalan and A. Povitsky, Stream Function-Potential Function Coordinates for Aeroacoustics and Unsteady Aerodynamics, Int. Journal of Computational Fluid Dynamics, Vol. 23, No. 3, pp. 285-290, 2009.

Comparison of vorticity contours by experiments(*) and present numerical simulations in pure pitch regime

(*)McGowan, G., Gopalarathnam, A., Ol, M., Edwards, J., and Fredberg, D. Computation vs. experiment for high frequency low-Reynolds number airfoil pitch and plunge, *46th AIAA Aerospace Sciences* , Reno, AIAA 2008-0653

	Experiment	Numerical
Bottom stroke	 (a)	 (b)
Top stroke		

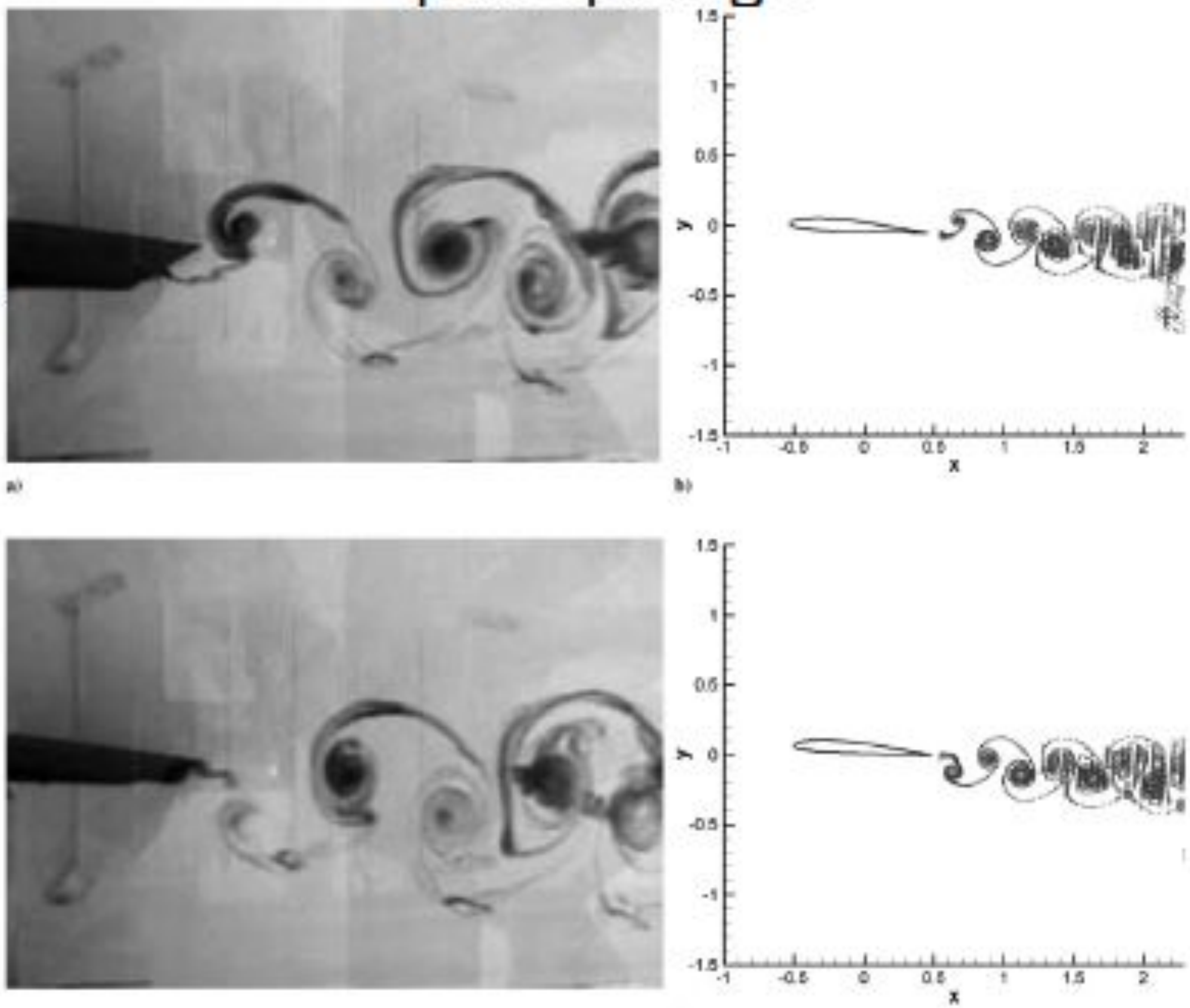
$\theta(t) = 4^\circ + 21^\circ \cos(2kt)$ *Re =10000, k =3.93, maximum angle 21 degrees*

Comparison between experimental (dye injection) and numerical particles' tracking for an SD 7003 airfoil in pure plunge

Experiment Numerical

Bottom stroke

Top stroke



Re =10*000*, *k =7.85*, h=0*.05 x chord length*

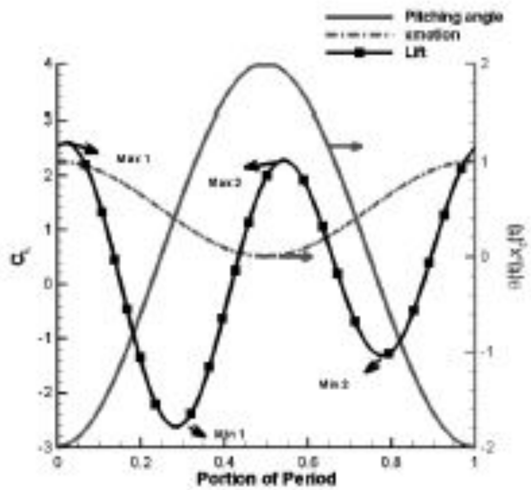
Average coefficient of lift for periodically moving center of rotation

Case	Average coefficient of lift, C_L	Average coefficient of thrust, C_T	Phase difference (*)	
Pitching about leading edge	0.25	-0.036	0	
MC1	0.23	-0.023	0	
MC2	**0.59**	-0.0002	90 degrees	the best lift!
MC3	0.204	-0.028	180 degrees	
Pitch and plunge	0.27	0.012	90 degrees	
Pitch-plunge with MC2	0.67	**0.017**	90 degrees	The best thrust!

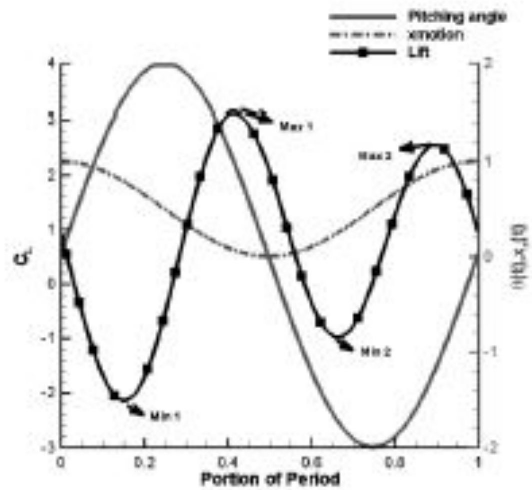
(*)The phase difference *is between the pitching angle and the motion of* the pitching axis

For the MC1 case ,the maximum (minimum) pitching angle is obtained when the instantaneous center of rotation is at the leading (trailing) edge.

Pitching angle, axis motion, and instantaneous coefficient of lift for the generalized pitching case: a) MC1, b) MC2, and c) MC3

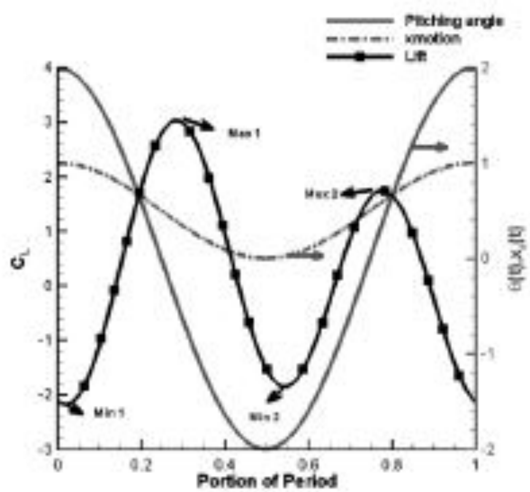


a)



b)

Two minima and two maxima over a period are caused by interaction of two sinusoidal functions with the same frequency: namely, motion of center of rotation and pitching motion.

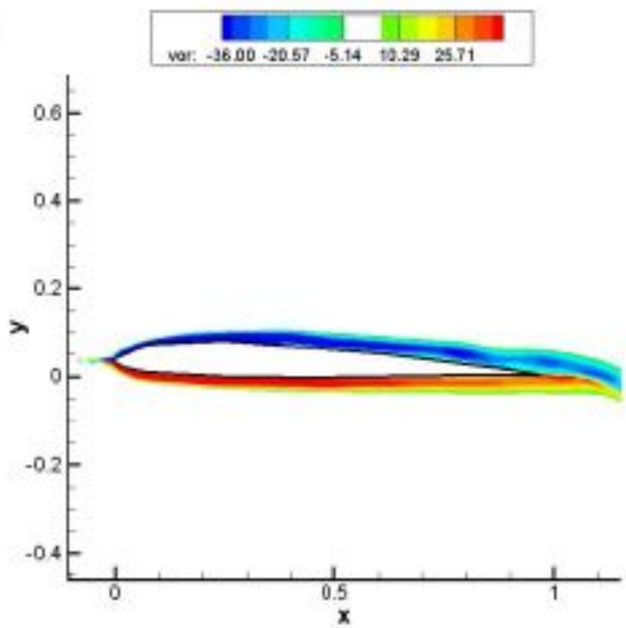


c)

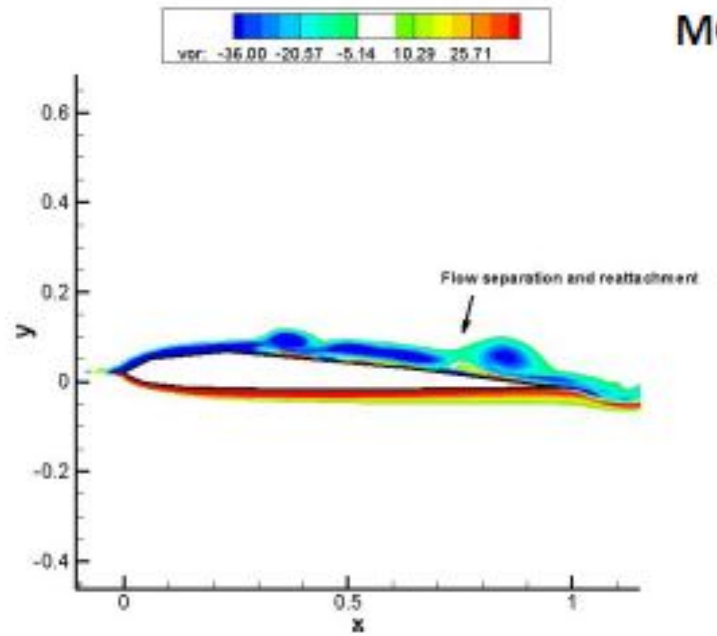
For the MC2 case, the pitching angle is zero degrees when the instantaneous centers of rotation are located at the leading edge and at the trailing edge.

Vorticity contours for MC1 and MC2

MC1



MC2



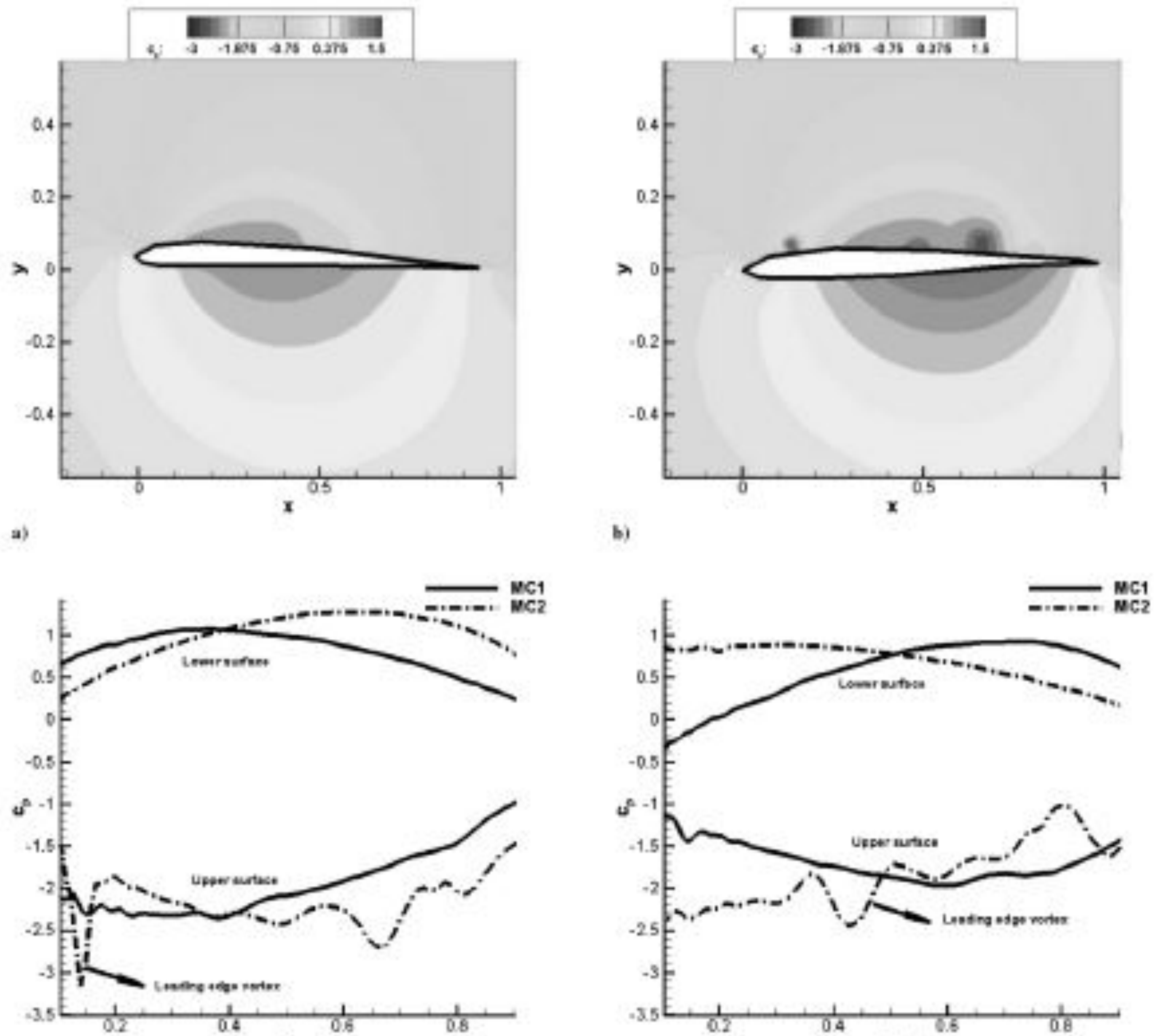
For the MC1, vorticity contours show that the flow remains attached to the airfoil everywhere except close to the trailing edge.

For the MC2, there is a visible separation of flow at the upper surface of the airfoil and reattachment. This cause a significant reduction in the instantaneous pressure field at the upper surface of the airfoil thereby resulting in the increase of the period-averaged coefficient of lift.

H. Gopalan and A. Povitsky, *Lift Enhancement of Flapping Airfoils by Generalized Pitching Motion*, AIAA Journal of Aircraft, Vol. 47, No. 6, pp. 1884-1897, 2010.

Comparison of the coefficient of pressure between MC1and MC2 cases of generalized pitching:

Time moment corresponds to local maximum of lift



Generalized Pitching:

1) Stable leading edge vortex (LEV) causes a higher value of the mean coefficient of lift for the MC2 case compared to the MC1 and MC3 cases.

2) Coefficient of lift for the MC2 case is more than two times higher than that for combined pitch–plunge motion with a phase difference of 90 degrees.

3) Combined pitch–plunge motion with a phase difference of 90 deg between them produces thrust, whereas the MC2 case produces drag.

4) MC2 case with an added plunge motion obtains higher mean value of lift than MC2 and produce thrust indicating the possibility of using superposition of kinematics motions of wings to generate the required lift and thrust forces.

Periodic gust effect on flapping motion

Average coefficient of lift	Plunging, h=0.025	Plunging, h=0.035	Plunging, h=0.045	Pitching, 4 degrees
No Gust	0.21	0.22	0.24	0.20
Presence of gust	0.177	0.151	0.13	0.187
Lift drop, %	16	32	46	7

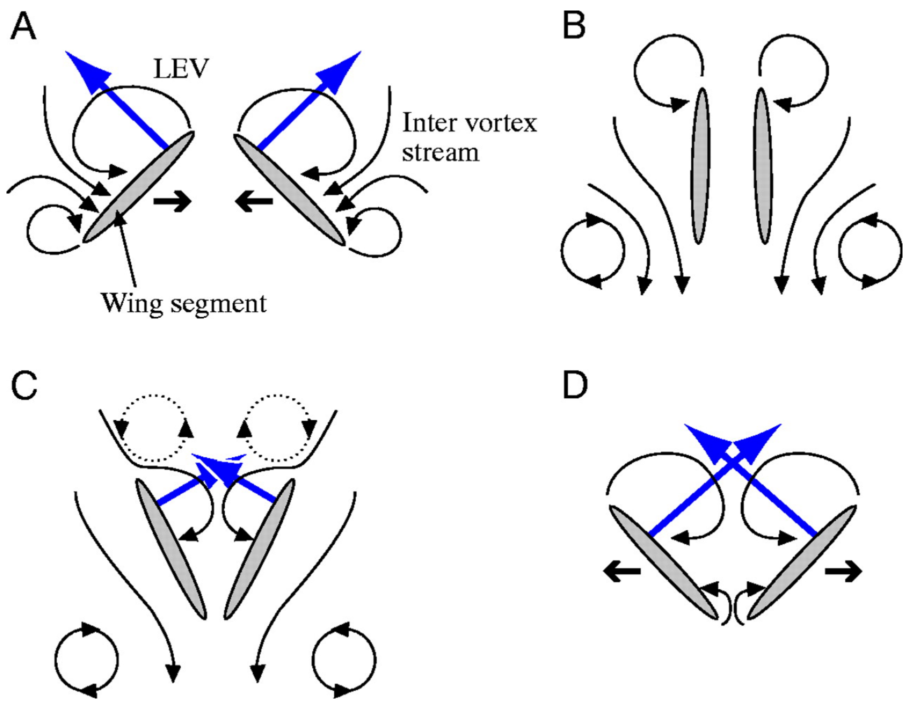
The plunging motion is very sensitive to the presence of the wind gust. Although the three cases gave approximately the same magnitude of the average coefficient of lift, the h=0.045 case showed a significant drop in lift in the presence of a wind gust.

The pitching motion shows less sensitivity to the out of phase wind gust. This suggests that the pitching motion is a good choice to cancel the effect of a wind gust in open terrain.

Why to use oscillating wings in turbomachinery?

slide *by Turbomachinery branch of NASA GRC*

Background: Pitching and plunging airfoils have been extensively studied for external flow applications with regards to flapping wing flight such as that of birds and insects. Applications include micro air vehicles. Rotational turbomachinery components have the benefit of maintaining rotational inertia. However, they are limited when the size of the parts begin to shrink as with the class of engines that might be used for the N+3 and beyond aircraft.



Hypothesis: Optimal spacing of ‘flapping’ blades in compressor could eventually get reasonable thrust comparable or better than that for rotating blades

- **Hypothesis:** Optimal spacing of ‘flapping’ blades in a cascade and/or in tandem can generate more thrust (compression) and lift (power extraction) than rotating components for the same weight by taking advantage of 3D vortex control, reduced tip leakage losses, no disks and shafts.

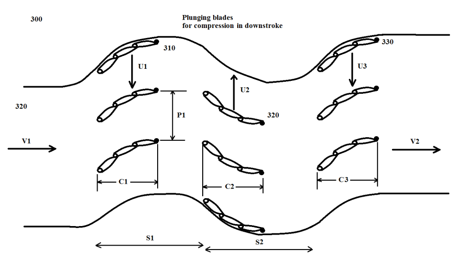


FIG. 7A

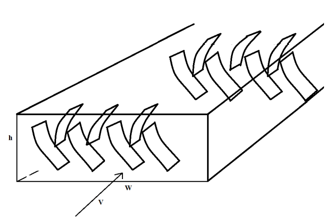
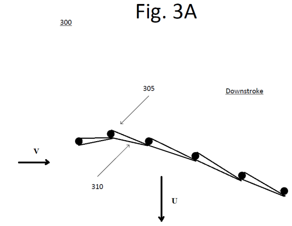


Fig. 3A

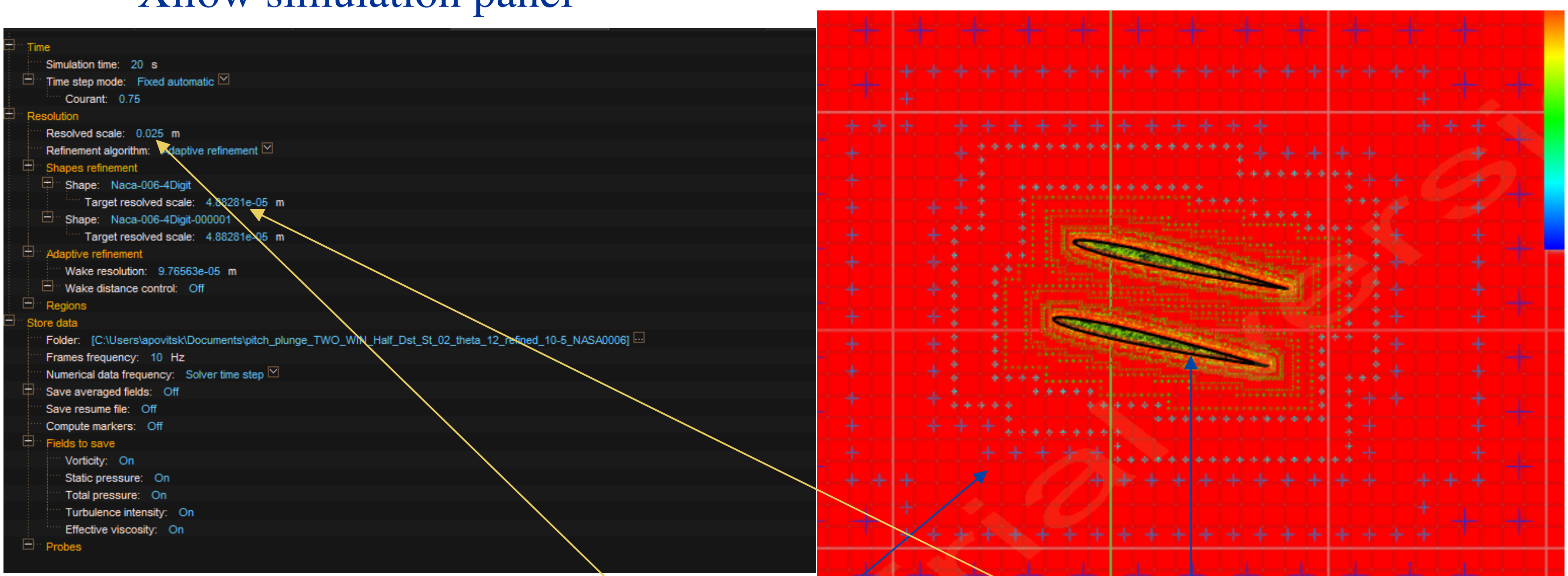


- The flapping motion is substantially larger by magnitude compared to that investigated in the first “MAV” part of presentation
- The presence of stationary solid walls and adjacent rows of blades makes the problem more challenging.
- Thrust generation (not lift) is a primary goal for compressor

Lattice Boltzmann method (LBM) and CFD software XFLOW

- **Approach:** Use CFD software XFlow - a particle-based kinetic Lattice Boltzmann method (LBM) specifically designed to handle complex multi--body motion and avoid classic domain meshing. The user can easily control the level of detail of the underlying lattice with a small set of parameters. http://www.xflowcfd.com/technology/view/cfd

Xflow simulation panel



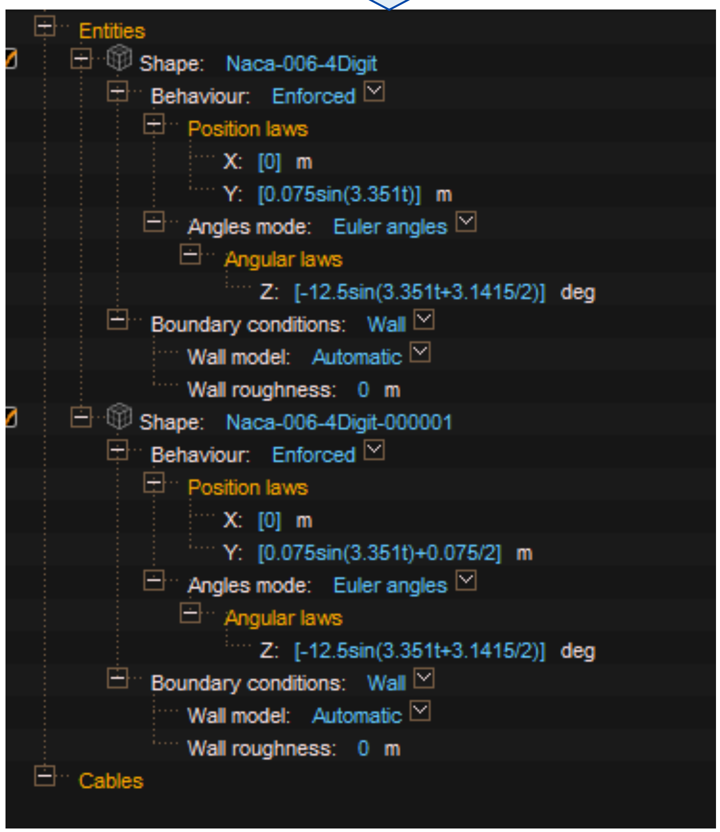
Coarse overall grid scale

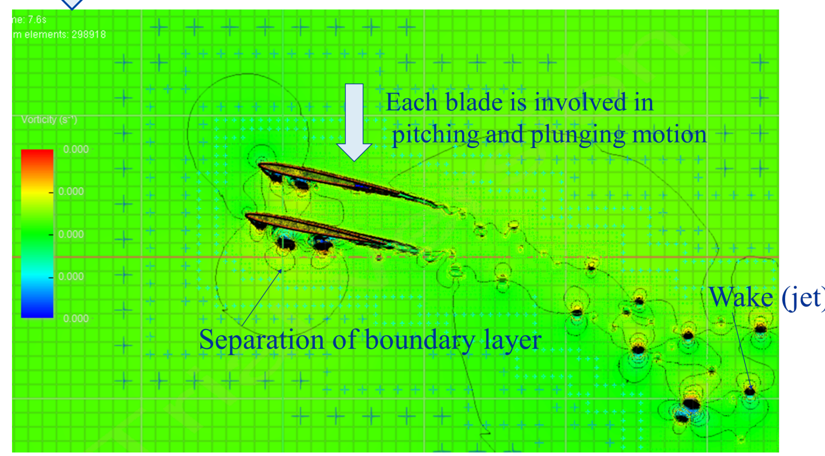
Refined scale

LBM and Xflow

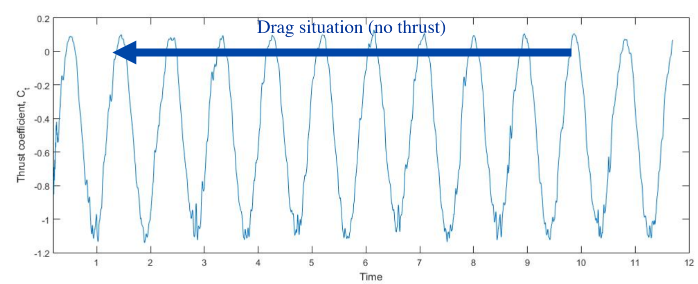
- The unsteady computational fluid dynamics around multiple bodies is potentially well captured by so-called Lattice Boltzmann Method (LBM).
- Unlike traditional CFD methods, which solve the conservation equations of macroscopic properties (i.e., mass, momentum, and energy) numerically, LBM models the fluid consisting of fictive particles, and such particles perform consecutive propagation and collision processes over a discrete lattice mesh.
- The LBM-based code XFlow is capable of handling complex geometry of ensemble of blades with nested Cartesian mesh with multiple resolution method. The 2-D or 3-D nested meshes are generated automatically by XFlow.
- The code use several approaches to turbulent flow including Spalart-Allmaras RANS model.

Input and Output of Xflow

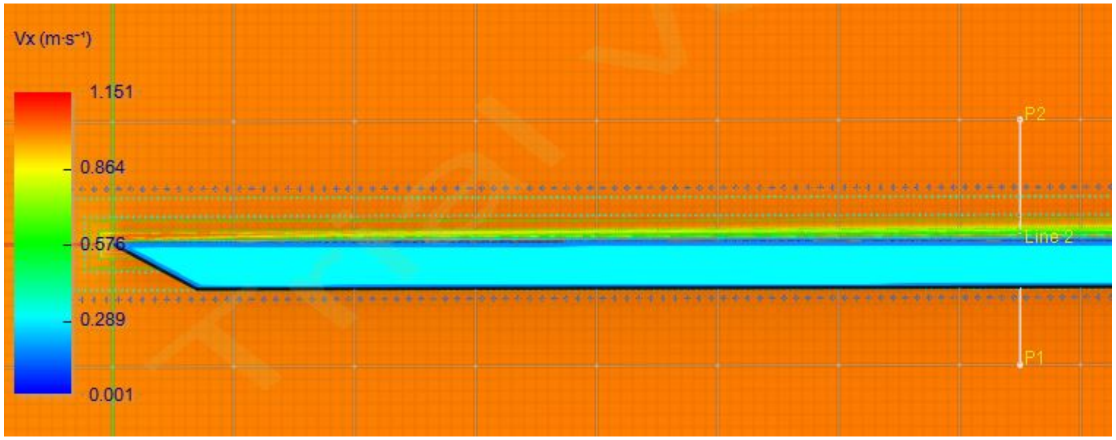




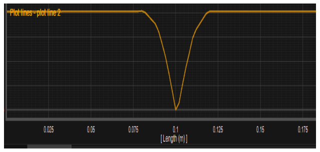
Composite Thrust coefficient



Selection of degree of refinement in boundary layer using analytical solution for flow over flat plate



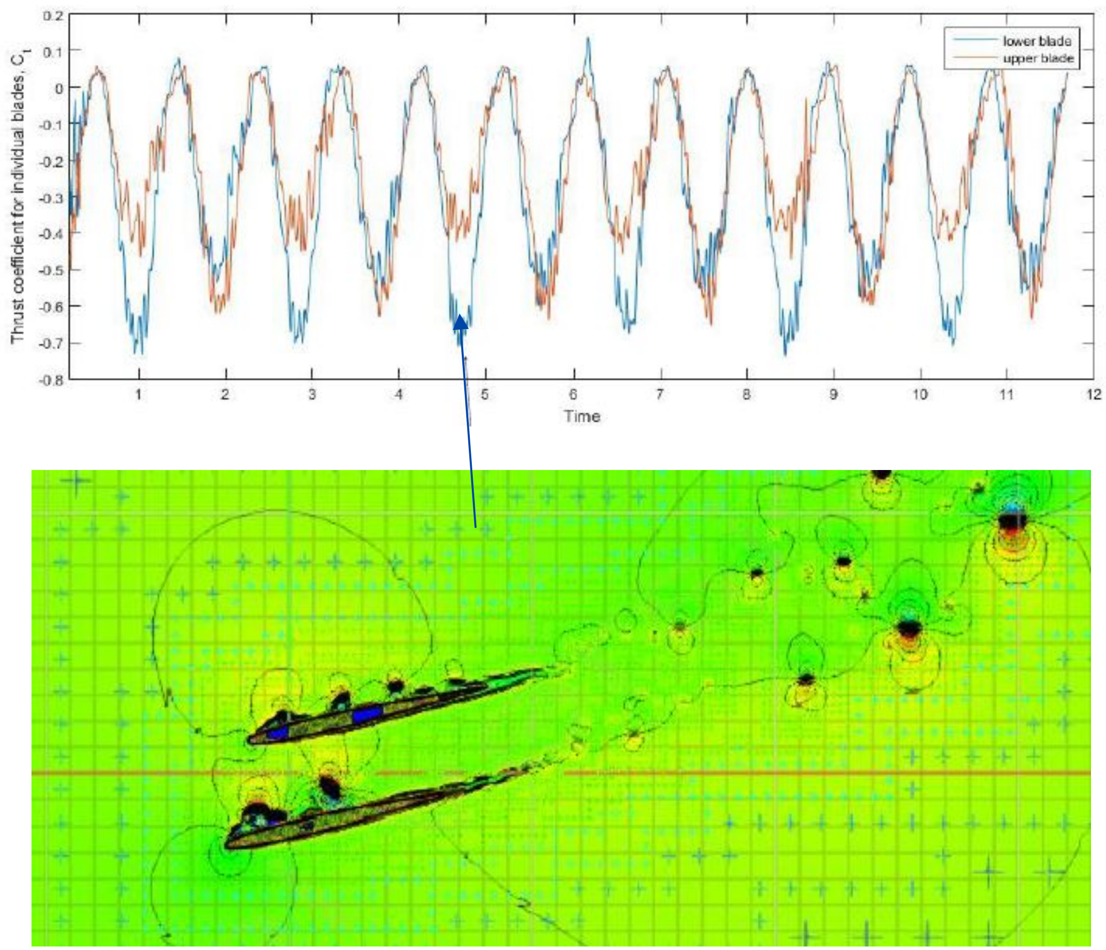
grid refinement



converging of drag coefficient to Blasius solution

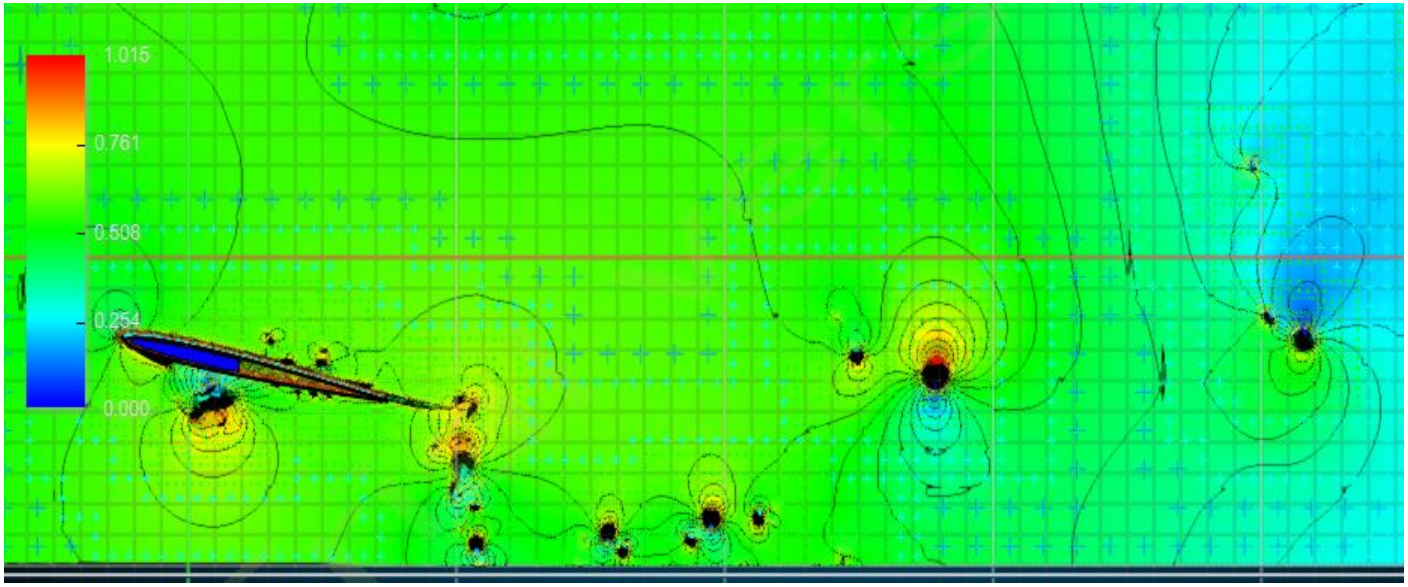
profile of boundary layer with plate located at 0.1

Thrust coefficient for each blade



Flowfield at the time moment of maximum thrust

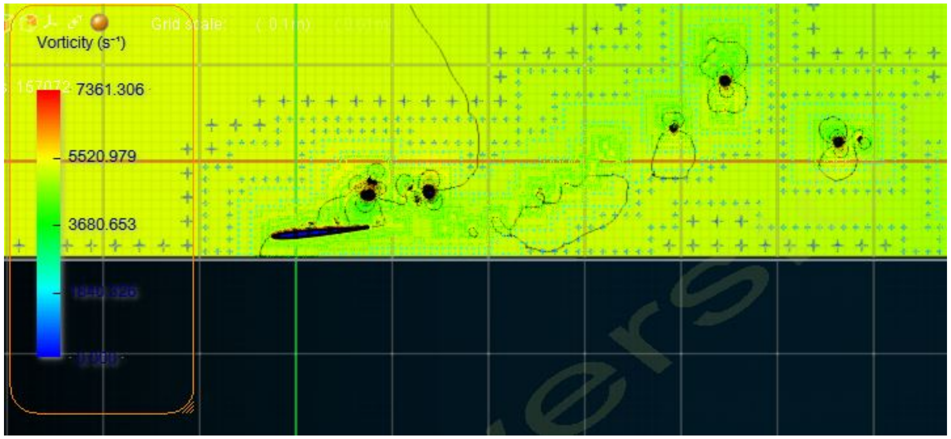
Periodic boundary conditions at horizontal boundaries:
flapping wing approaching lower boundary is shown



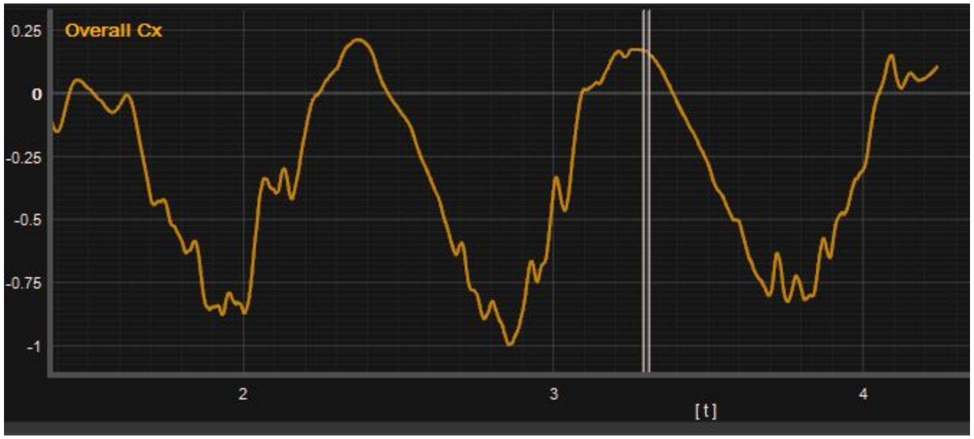
To mimic sets of multiple blades, the periodic boundary conditions were tested. Vortices coming from the next blade are clearly seen.

Flapping wing at proximity to wall

vorticity contours at maximum drag at proximity to wall

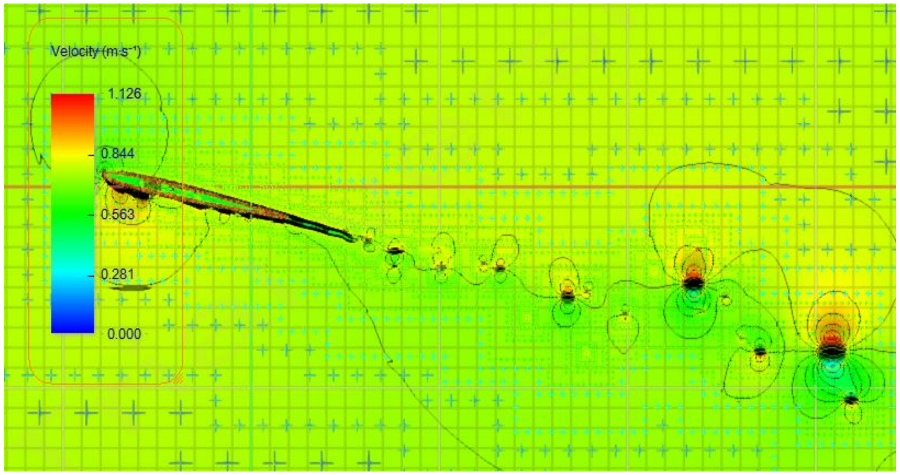


thrust coefficient as a function of time

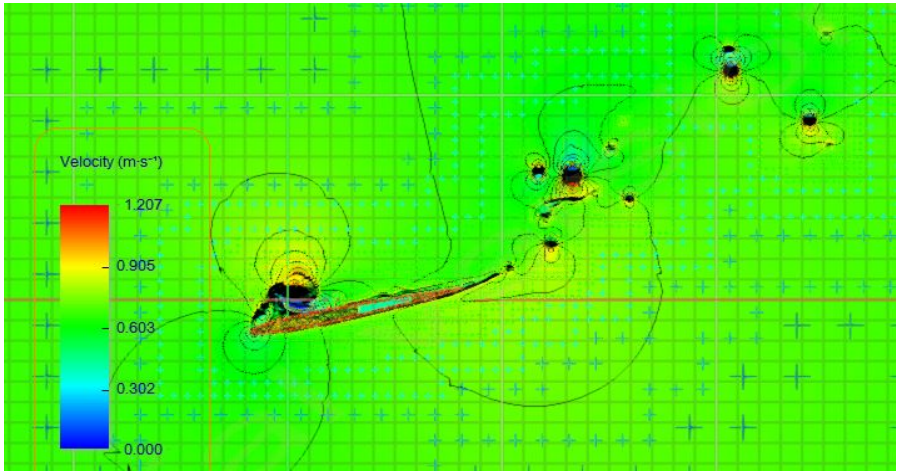


Moving instantaneous center of pitching

C_T=0.6



C_T=0.4



In prior cases the center of pitching rotation has been fixed at a distance of 1/3 of chord. Here the instantaneous center of rotation has been moved back and forth between the leading edge and trailing edge of the blade.

Parametric investigation

- Considered blade profile was NACA0006 with 6% thickness. Compared to NACA0012, this profile generated bigger thrust because of easier separation of boundary layer rolled into stream of discrete vortices.
- The amplitude of plunging was selected equal to 75% of chord length; in the future research the amplitude of plunging can be adjusted to adhere to geometry of channel.
- Angular amplitude of pitching was selected 12.5 degrees. Note that our initial attempts to use larger amplitude of pitching as recommended in reference below leads to generation of drag instead of thrust.
  F.S. Hover, Ø. Haugsdal, and M.S. Triantafyllou, Effect of angle of attack profiles in flapping foil propulsion, Journal of Fluids and Structures 19 (2004) 37–47
- Phase difference between plunging and pitching motions was selected equal to 90 degrees, the variation of phase difference between 75 and 105 degrees did not lead to variation of thrust. The distance between two blades in parallel setting was selected equal to 50 % of magnitude of plunging. Phase difference between motions of two blades in parallel setting was presently set equal to zero to allow blades move with the same distance between them at any time moment.

Considered blade profile was NACA0006 with 6% thickness. Compared to NACA0012, this profile generated bigger thrust because of easier separation of boundary layer rolled into stream of discrete vortices. The amplitude of plunging was selected equal to 75% of chord length [4]; in the future research the amplitude of plunging can be adjusted to adhere to geometry of channel or optimization of thrust. Angular amplitude of pitching was selected 12.5 degrees. Note that our initial attempts to use larger amplitude of pitching as recommended [4] leads to generation of drag instead of thrust.

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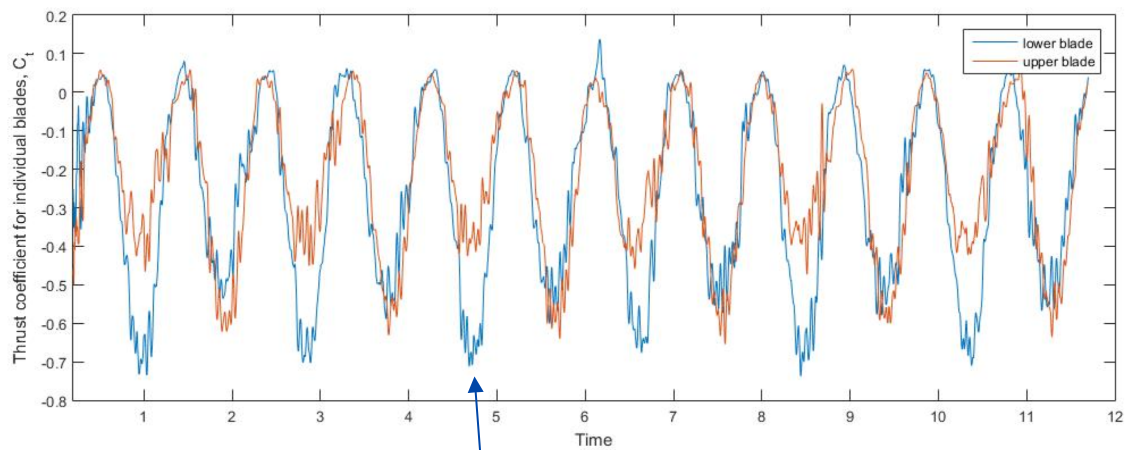
Selected values of governing parameters include:

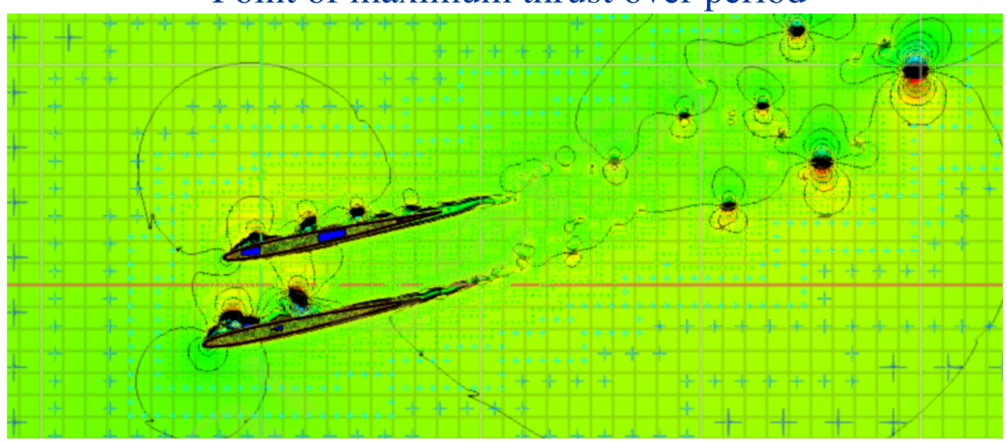
- blade profile and thickness (NACA0006 is adopted)
- amplitude of plunging (0.75 x chord length)
- angular amplitude of pitching (12.5 degrees)
- phase difference between plunging and pitching (90 degrees)
- distance between blades (0.5 x plunging amplitude)
- Phase difference between two blades (0 degrees)

Dynamics of thrust

Individual airfoil thrust coefficient



Point of maximum thrust over period



Conclusions: Part 1. High-order FD modeling

1. The numerical model of aerodynamics of flapping airfoils in generalized pitching motion has been developed based on the high-order approximation of derivatives in numerical solution of Navier–Stokes equations. Non-inertial coordinate system attached to the moving airfoil was used.
2. Comparison of numerical results for pitching and plunging motions of the airfoil with the experimental data by Dr. M. Ol (AFRL) and his collaborators showed good agreement in terms of streamwise velocity, vorticity, and wake velocity profile.
3. The pure-pitch case was considered for the pitching axis located at different points along the chord. The maximum mean coefficient of lift was obtained when the pitching axis was at the leading or trailing edge. The momentary lift appears to be an order of magnitude higher than steady lift caused by the angle of incidence; however, the time-averaged value of lift is only moderately higher than that for steady flight.
4. The generalized pitching motion was studied for three different phase differences between the pitching amplitude and the motion of the axis. It was found that the use of quasi-steady approximation leads to significant error in the estimate of lift coefficient, therefore, CFD computations are essential for the generalized pitching motion of wings.

Continuation of conclusions: Part 1. High-order FD modeling

5. It was found that the maximum mean coefficient of lift was produced when the phase difference was 90 deg. The value of lift was found to be more than doubled compared to that obtained by combined pitch–plunge motion.
6. However, unlike the combined pitch–plunge motion, the generalized pitching motion did not produce thrust. To obtain thrust, modified kinematic motion that adds a plunging motion to the generalized pitching motion was proposed and investigated.
7. This superposition of the motions increased the value of the lift coefficient compared to a generalized pitching motion. Further, it also generated thrust force that supports the use of superposition of complex kinematic motions to obtain a needed amount of lift and thrust.
8. The study of the effect of a sinusoidal vortical gust on the lift revealed that the pitching motion of the airfoil is less sensitive to the gusty conditions compare to plunging.

Conclusions: Part 2. Xflow LBM simulation of flapping blade

1. Commercial LBM-based code Xflow was studied and tested for set of tests.
2. Values of LBM refinement parameter for near-wall boundary layer and downstream wake were evaluated by comparison to known analytic/ numerical solutions. This value largely determines amount of computational resources needed.
3. For pair of blades range of proximities between blades in the transversal to flow direction was considered.
4. Effect of proximity of wing to stationary wall in terms of thrust was evaluated .

Near future research:

- Include additional effects of endwalls/channel housing
- Study of relative phase of adjacent phase/blade on thrust generation
- Optimization of thrust generation by multiple blades in 3-D geometry of compressor.
- Advanced program of blade motion such as that with variable center of rotation
- Comparison of efficiency of LBM to high-order schemes on moving structured grids (see H. Gopalan and A. Povitsky, AIAA J. of Aircraft, Vol. 47, No.6, 2010)

Publications

- A. Povitsky, Modeling of Pitching and Plunging Blades and Cascades for Thrust Generation, submitted to AIAA Aviation 2016
- H. Gopalan and A. Povitsky, Lift Enhancement of Flapping Airfoils by Generalized Pitching Motion, AIAA Journal of Aircraft, Vol. 47, No. 6, pp. 1884-1897, 2010.
- H. Gopalan and A. Povitsky, Stream Function-Potential Function Coordinates for Aeroacoustics and Unsteady Aerodynamics, Int. Journal of Computational Fluid Dynamics, Vol. 23, No. 3, pp. 285-290, 2009.
- H. Gopalan and A. Povitsky, A Numerical Study of Gust Suppression by Flapping Airfoils, the 26thAIAA Applied Aerodynamics Conference, AIAA Paper 2008-6394.
- Gopalan, H., "Numerical Modeling of Aerodynamics of Airfoils of Micro Air Vehicles in Gusty Environment," P h.D. Dissertation,Department of Mechanical Engineering, Univ. of Akron, Akron, OH, 2008. Advisor: A. Povitsky. Web : http://etd.ohiolink.edu/
- H. Gopalan and A. Povitsky, High-order method for modeling of aerodynamics of flapping wings: Airfoil-gust interaction, in Proceedings of "Advances in Mathematical and Computational Methods "(AMCM), Waterloo, CA, 2011, pp. 105-109

Use of a Pitching and Plunging Cascade for Thrust Generation

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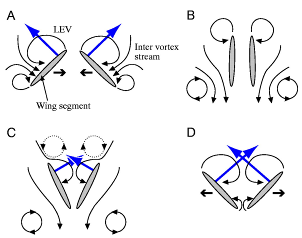
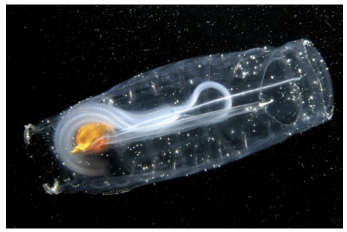
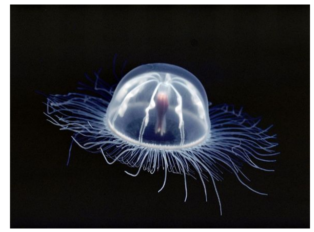
Department of Mechanical Engineering, The University of Akron, Akron OH
NASA Sponsors: Dr. Vikram Shyam, Dr. Mark Celestina
Turbomachinery and Turboelectric Systems Branch, NASA GRC

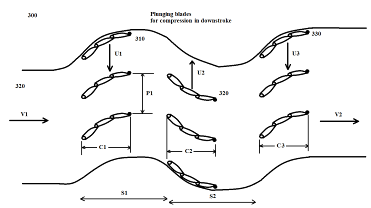
Background: Pitching and plunging airfoils have been extensively studied for external flow applications in regards to flapping wing flight such as that of birds and insects. Applications include micro air vehicles, ornithopters and entemopters. Insects such as flies and butterflies use the Weis-Fogh mechanism. Rotational turbomachinery components have the benefit of maintaining rotational inertia they are limited when the size of the parts begin to shrink as with the class of engines that might be used for the N+3 and beyond aircraft.







Hypothesis: Optimal spacing of ‘flapping’ blades in a cascade and/or in tandem can generate more thrust (compression) and lift (power extraction) than rotating components for the same weight by taking advantage of 3D vortex control, reduced tip leakage losses, no disks and shafts. In addition, such a system is a more natural fit for propulsions systems that use pressure gain combustion.



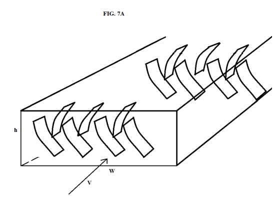
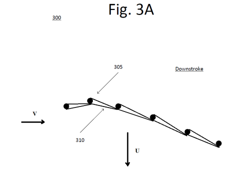
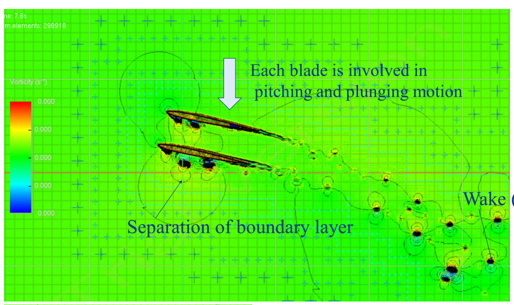


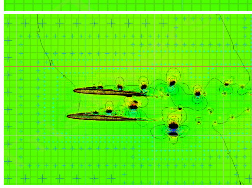
Fig. 3A

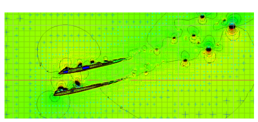


Results:

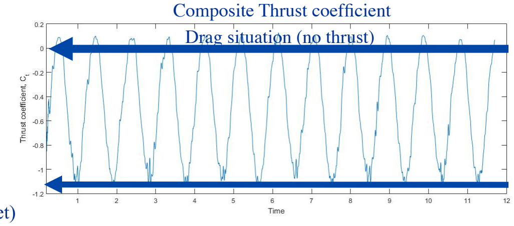


Wake (jet)

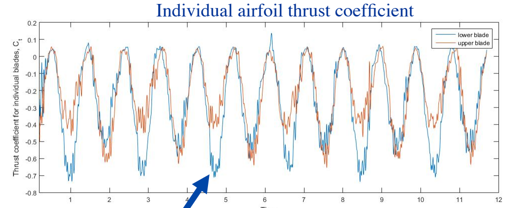




Composite Thrust coefficient



Individual airfoil thrust coefficient



Maximum thrust over period

Approach: Use CFD software XFlow - a novel particle-based kinetic Lattice Boltzmann method (LBM) specifically designed to handle complex multi--body motion, avoid classic domain meshing. The user can easily control the level of detail of the underlying lattice with a small set of parameters.
http://www.xflowcfd.com/technology/view/cfd

Objectives: Compare pitching plunging airfoil to cascade of pitching plunging airfoils to maximize thrust. Compare pitching plunging airfoil thrust to rotating airfoil thrust

Governing parameters include:
- blade profile and thickness (NACA0006 is adopted)
- amplitude of plunging (0.75 x chord length)
- angular amplitude of pitching (12.5 degrees)
- phase difference between plunging and pitching (90 degrees)
- distance between blades (0.5 x plunging amplitude)
- Phase difference between two blades (0 degrees)

Future research:
- Include effects of endwalls/channel housing
- Include tandem bladerows
- Study of relative phase of adjacent phase on thrust generation
- Optimization of thrust generation by multiple blades in 3-D geometry of compressor.
- Comparison of efficiency of LBM to high-order schemes on moving grids (see H. Gopalan and A. Povitsky, AIAA J. of Aircraft, Vol. 47, No.6, 2010)

Gust details

In this section the effect of wind gust on SD 7003 airfoil in pure-pitch and pure-plunge motions are investigated. To avoid the necessity to implement special boundary conditions, a vortical gust is added as a source term to the right hand side of the Navier-Stokes equation[111]. The source term and the coefficients C_1, C_2 are computed from the following formulas

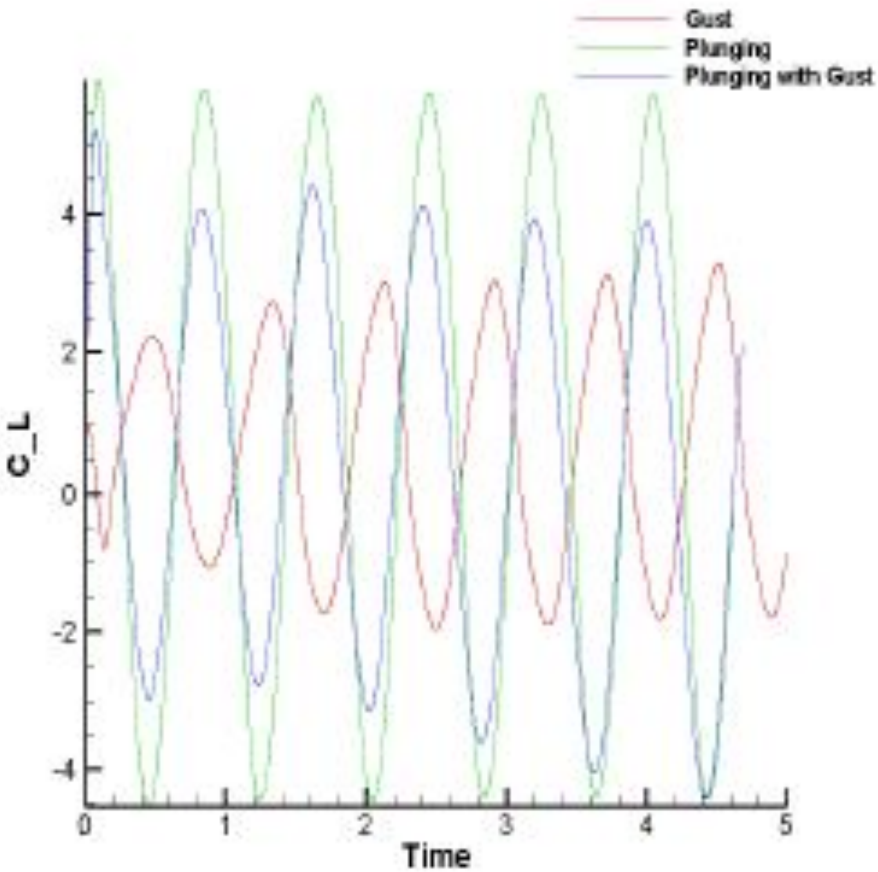
$$S = \begin{pmatrix} 0 \\ C_1 \cos(kt) \\ C_2 \cos(kt) \\ 0 \end{pmatrix} \tag{6.1}$$

$$C_1 = 3a(1 + \cos(b(x - x_c)))(tanh(3(y + y_c))^2 - tanh(3(y - y_c))^2) \tag{6.2}$$

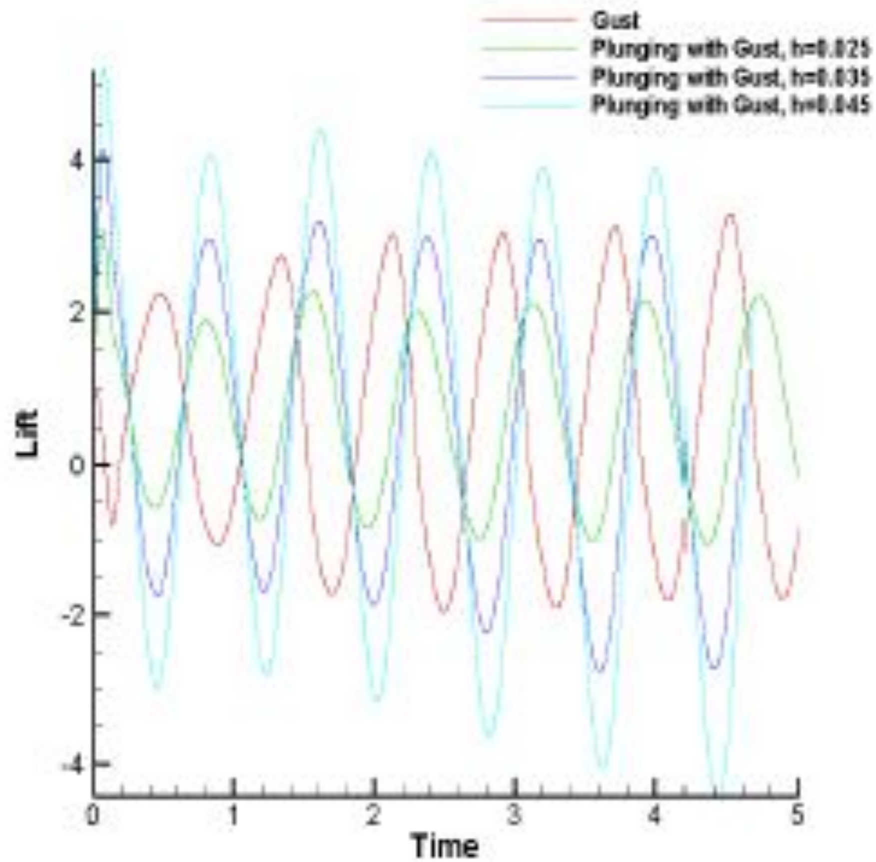
$$C_2 = ab \sin(b(x - x_c)))(tanh(3(y + y_c) - tanh(3(y - y_c)) \tag{6.3}$$

in the range $|x - x_c| \leq \frac{\pi}{b}$ and 0 outside the range. In the above equations, a represents the gust amplitude, b represents the gust width, (x_c, y_c) represents the center of the vortical gust. The magnitude of the other parameters in (6.2,6.3) are given by $x_c = -1.2, y_c = 0.1, b = 5, a = 1.8$.

[111] D.P. Lockard and P.J. Morris. Radiated noise from airfoils in realistic mean flows. *AIAA Journal*, 36(6):907–914, 1998.



(c)h=0.045



(d)Comparison between the three cases

Figure 6.9: Comparison of the coefficient of lift for different plunging amplitudes at $k = 3.93$

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Force Evaluation in the Lattice Boltzmann Method Involving Curved Geometry

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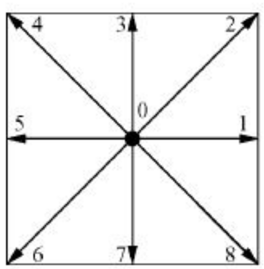


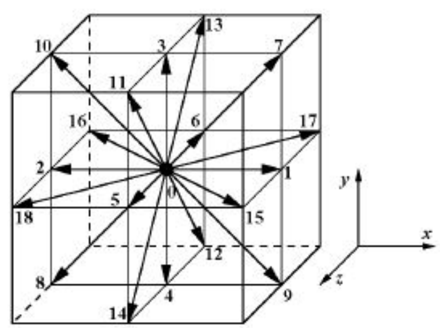
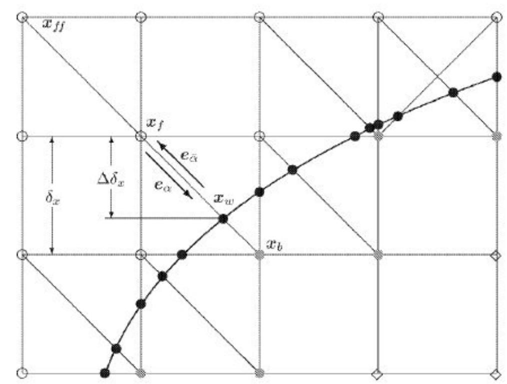


FIG. 1. *Discrete velocity set* $\{\boldsymbol{e}_\alpha\}$. (left) *Two-dimensional nine-velocity* (D2Q9) *model.* (right) *Three-dimensional nineteen-velocity* (D3Q19) *model.*



Layout of the regularly spaced lattices and curved wall boundary. The circles (○), *discs* (●), *shaded discs* (∗), *and diamonds* (◇) *denote fluid nodes, boundary locations* ($\boldsymbol{x}_w$), *solid nodes which are also boundary nodes* ($\boldsymbol{x}_b$) *inside solid, and solid nodes, respectively.*